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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT 271

Technical Evaluation Report on Aerodynamics of Combat Aircraft Controls and of Ground Effects

(L'Aérodynamique des Commandes des Avions de Combat et des Effets de Sol)

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Technical Evaluation Report on
Aerodynamics of Combat Aircraft Controls and of Ground Effects

(L'Aérodynamique des Commandes des Avions de Combat et des Effets de Sol)

by

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Foreword

The complex shapes of modern combat aircraft, in combination with ever-widening flight-envelopes and increasing demands for greater manoeuvrability and controllability, have intensified the need to improve the aerodynamic design of aircraft controls. However, the basic understanding of aerodynamic controls is still deficient in many areas and aircraft designers are still very dependent on results from wind tunnels and flight tests. Though computational methods are proving increasingly effective in basic vehicle design, application to controls has met with limited success because of the dominance of unsteady viscous and separated-flow effects, which lead to poorer control performance than predicted, often coupled with high buffet levels.

It was the purpose of the Symposium to review the aerodynamic design of controls at take-off and landing conditions, for manoeuvring at subsonic, transonic and supersonic speeds, for high angles of attack and yaw, and for departure prevention and post-stall manoeuvring. Also, part of the Symposium was concerned with novel control devices. With regard to ground effects, computational and experimental methods were reviewed, and included jet effects on flow-field forces and intake flows.

Avant-Propos

Les formes complexes des avions de combat modernes, associées aux domaines de vol qui s'étendent sans cesse et aux demandes croissantes pour une plus grande manoeuvrabilité et une plus grande contrôlabilité, ont fait croître le besoin d'améliorer les moyens de conception et de définition de leurs gouvernes.

Cependant les connaissances de base sur le fonctionnement des gouvernes sont encore insuffisantes sur bien des points et les concepteurs d'avions doivent encore se reposer beaucoup sur les résultats d'essais en soufflerie et en vol. Bien que les méthodes de calcul se montrent de plus efficaces pour les projets, leur utilisation pour les gouvernes a un succès limité à cause de l'importance des effets visqueux et de la présence de décollements qui conduisent à des performances inférieures à celles qui sont calculées et, en plus, à des niveaux de tremblement élevés.

C'était le but de ce symposium que de faire le point sur la définition aérodynamique des gouvernes:

— dans les configurations de décollage et d'atterrissage,

— pour les manoeuvres en subsonique, transsonique et supersonique,

— pour les grands angles d'attaque et de dérapage,

— pour la prévention de la mise en vrille,

— et pour les manoeuvres après décrochage.

Une partie du symposium a également été consacrée aux nouveautés en matière de controle aérodynamique.

En ce qui concerne l'effet de sol, les méthodes expérimentales et les méthodes de calcul ont été passées en revue. Leur aptitude à évaleur les effets de jet sur les efforts aérodynamiques et sur les écoulement d'entrée a été examinée.

D.H. Peckham and J. Leynaert
Co-Chairmen

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1. INTRODUCTION

The first theme of this symposium addressed the issue that new requirements are emerging for combat aircraft for offensive and defensive maneuvers, which include high angles of attack and yaw, and a greatly expanded flight envelope, with high acceleration rates in all axes of flight.

The second theme of this Conference was ground effects on combat aircraft aerodynamics and control. This is always important, but much more so when thrust vectoring and reverse is used on landing approach or for short takeoff.

These two themes were given a thorough examination at the conference through the outstanding papers that were presented, and the formal and informal discussions that followed.

2. FUTURE REQUIREMENTS

References 2 and 4 clearly showed that new aircraft control requirements will be dictated by extreme maneuvers at very high rates; for example, rapid rolling maneuvers around the velocity vector will be used to rapidly change the plane of attack of the aircraft.

During rapid maneuvering, many of the aerodynamic control surfaces are undergoing time-dependent separation which can induce non-linearities in the aerodynamics of the aircraft and its control system. It was pointed out that there was often times difficulty in obtaining both dynamic stability and favorable damping, while still maintaining a high level of agility. Active control of forebody, wing, and canard vortices seems to be the key.

Skow, presenting ref 4 paper, pointed out that another requirement for controls, for increased maneuverability/agility in the aircraft, is the strong requirement for nose down pitching moment control at high angle of attack. Nose-down pitch control is needed to arrest a nose-up maneuver, to quickly unload to reduced G's (to be able to accelerate), and to control pitch-due-to-rolling about the velocity vector at high angle of attack. It is impossible to keep the nose pointed precisely unless there is adequate nose-down pitch control. Most configurations have much more nose-up pitching moment capability than nose-down authority.

It was pointed out by several authors (refs 2, 4, 11) that an important factor in controls for agile aircraft is lateral-directional control at high angle of attack and high alpha rates. To initiate desired maneuvers, and to stop undesired maneuvers, is often difficult because the tail, especially the vertical fin, has decreased effectiveness at high angle of attack.

In order to support advancements in fundamental understanding of controllability at extreme maneuvers, we will need to develop new methods of analysis and test. It was pointed out by Orlik-Rückemann in the round table discussion at the conclusion of the conference, that at combined high angles of attack with high angular rates, moderate angles of side slip or larger amplitudes of motion, a situation will be reached where the whole stability and control domain will become non-linear and, therefore, no longer describable by the relatively simple linear concept of stability derivatives. Aerodynamic effects will no longer be superimposable. Experimental evaluation will require a much more robust body of information on cross-coupling effects from rotary and forced oscillation balances.

3. CURRENT CONTROL DESIGN EXPERIENCE

References 5 through 8 summarized current control design experience, with emphasis on close-coupled canard/wing interactions at high angles of attack and at low speed during takeoff and landing. Reference 7 by Hummel and Oelker, is noteworthy for its low speed data.

Bufacchi, et al (ref 5), pointed out that, even for a relatively conventional aircraft configuration (Aermacchi AMX), data from the dynamic/rotary balances showed important differences from the static balance data. While the fixed balance results often tended to mask the effects of control deflection near the stall, the rotary balance allowed these to be quantified quite easily. In fact fixed balance results can be misleading because they tended to show rapid fluctuations due to asymetry of the stall which could mistakenly be ascribed to changes in control effectiveness. The authors of ref 5 also pointed out that employing differential canard deflections at high angle of attack could be used to improve directional stability.

Lovell (ref 6) provided a systematic investigation of various canard, wing and aft-tailplane arrangements, and concluded that optimum lift-to-drag ratio is achieved with trailing edge flaps deflected on a three-surface (canard-wing-tail) configuration.

Ref 8 pointed out that canard-wing configurations can have undesirable pitch-up (reduced stability) and lateral stability problems when the nose vortex burst is asymmetric, although the latter problem is not limited to canard configurations. Ref 8 authors also found some indications that dynamic (inertia) effects are important, especially at high angle of attack.

The general conclusion of this session of the symposium seemed to be that even though the control and aerodynamic characteristics of relatively conventional configurations are well understood at low or medium angles of attack, there are still some surprises when angles of attack approach stall, or when high onset rates are experienced. Careful experimental and analytical investigations need to be conducted to design the controls for performance and flight safety.

4. INNOVATIVE CONTROL CONCEPTS

Combat aircraft controls which work well in the "heart of the envelope" (medium maneuvering levels and medium speeds) are often deficient in providing responsive control authority in all axes at conditions of high angles of attack/yaw or where high accelerations about the axes of flight are required. It is at these conditions where innovative control concepts are needed. References 9 through 15 addressed various means of aerodynamic control augmentation through thrust vectoring, boundary layer suction or blowing, vortex formation/burst control, and geometry shaping or deployment of special surfaces. Properly so, the effects of unsteady aerodynamics were accounted for in the studies reported, although it is clear that much more work remains, particularly with regard to dynamic stability. Since the control effects are highly non-linear and time-dependent, caution is urged before some of these innovative control techniques can be considered in combat aircraft design. More data is needed at full scale Reynolds numbers from flight research.

4.1 High Angle of Attack Controls

Staying close to variations in conventional design control surfaces such as canards, wing shape, fuselage cross-section and tailplane components, ref 9 by Marks and Hahne showed that the maneuvering envelope could be increased considerably by careful integration of the aforementioned control components. Non-axisymmetric fuselage/nose shapes to prevent asymmetric vortex formation improved stability but also introduced negative damping in pitch. Vertical tail surfaces placed outboard on the wings gave good lateral-directional stability due to favorable interference with wing vortices, but could cause aero-elastic problems. In-board canting of vertical tails (probably to reduce signature) was found to be unstable in lateral-directional control, whereas out-boand canting was found to be favorable. Skewed hingeline tiperons provided increased roll control on highly swept, low aspect ratio wings up to post-stall angles of attack, although again there could be structural and weight issues. All-moveable twin vertical tails provided a substantial increase in yaw control over conventional rudders and thus extended roll coordination capability to higher angles of attack. However, the adverse roll generated by all-moveable vertical tails could present a potential problem, depending on the level of roll acceleration required and the roll control available from other surfaces.

Malcolm, et al, (ref 10) provided a good summary of the powerful effects of manipulation of the fuselage forebody vortex at high angles of attack through forebody strakes and by blowing air from a simple port (not a slot) on the forebody. Strakes located just above the horizontal axis of the forebody cross section were found to be very effective, but would probably have to be "deployable" to avoid drag penalties at lower angles of attack, and to produce yawing moment at high angles of attack. Forebody blowing experiments showed that aft blowing is most effective closest to the tip of the forebody and at a location on the leeward side approximately 135 degrees from the windward side, while forward blowing is more effective at a farther aft position from the tip at the same meridian. Blowing forward showed that at low blowing rates the yawing moment was in a direction opposite to the side where blowing occurred. At higher blowing rates the yawing moment was on the same direction as the blowing side. Aft blowing produced a yawing moment in the direction of the blowing side for all blowing rates and the moment continually increased with increased blowing. The level of yawing moment could be controlled by variation in the blowing rate on both sides individually. Differential blowing with one side forward and one side aft was very effective in producing controllable yawing moments. It was concluded that the most effective method to control the yawing moment on the forebody was to minimize the natural asymmetry with a pair of symmetrically mounted tip strakes and to perturb the vortex system away from the symmetric condition with blowing on either side. Thus, a combination of forebody strakes and blowing was found to be the most effective control device.

Overall, significant yawing moments (twice that available from the rudder at low angles of attack) can be produced at high angles of attack by either independently moving a pair of forebody strakes or by independently controlling blowing rates from ports located on the model surface.

Although these results are encouraging, they are based on static data at low speed conditions with laminar flow on the forebody. Further research should be conducted on the dynamic effects and evaluations at higher Reynolds number. A large scale drop model flight test should be considered.

Roberts and Wood (ref 11), evaluated slot blowing along the leading edge of a delta wing. The wing leading edge was fairly blunt, probably representative of a subsonic combat aircraft, although the results could, in principle, apply to thinner leading edges. Blowing on one side of the leading edge was found to produce high rolling moments at angles of attack approaching 50 degrees, so a device of this type could be used to augment control to roll about the velocity vector at high angles of attack and to prevent departure or wing rock at high alpha. The same blowing principle, if proven effective at flight conditions, could apply to other control surfaces to increase their effectiveness. Blowing rates will need to be evaluated at flight conditions to determine the amount of blowing coefficient (jet momentum normalized by dynamic pressure times wing area) required. Nevertheless, the results to date are encouraging.

Walchli (ref 12) discussed the unique X-29 forward swept wing configuration. Results obtained since this paper was presented at the symposium have shown that the X-29 is extremely stable and controllable about all axes at angles of attack up to 45 degrees. Pitch transients have been made to 65 degrees where the X-29 vertical tail is virtually ineffective. Ailerons on the forward swept wing are still effective, even at this extreme angle of attack, and provide the ability to stabilize the pitch, but not enough to roll about the velocity vector. Apparently the forward swept wing , full authority canards and the small pitch surfaces adjacent to the vertical tail are more effective in flight than was expected from the wind tunnel data.

4.2 Dynamic and Unsteady Effects

Hancock and Mabey (ref 13) provided keen fundamental insight into control response for surfaces with attached flow. This is especially important for active controls associated with statically unstable aircraft. Another application is design criteria for flutter suppression systems. For "fast acting" controls, where the time of deflection of the control surface is on the order of the flow transit time over the surface, the understanding of unsteady aerodynamic effects is critical. Computational fluid dynamic analysis, with time-accurate unsteady flow solvers, is being developed in several of the AGARD member nations. Perhaps the phenomena observed by Hancock and Mabey, wherein the aerodynamic rise time to attain steady state conditions was found to decrease abruptly near Mach 1, can be predicted in the not-so-distant future. Ref 15, Bearman and associates, gave some encouragement for this possibility with their analysis of a rapid spoiler deployment on a two-dimensional airfoil, albeit for incompressible, inviscid flow. Ref 14, by Mabey, et al, evaluated the effects of an unsteady canard flow, such as would be the case if a canard was used for active control of an unstable aircraft (pitch axis), and found that, for the configuration investigated, canard oscillations with one degree amplitude had virtually no detrimental effect on the mean flow of the wing. X-29 flight experience has essentially verified this conclusion. Thus active control using canards can be considered for combat aircraft although test verification would clearly be required.

4.3 Thrust Vectoring Controls

Thrust vectoring for combat aircraft, using the main engine(s) is now being considered to produce forces and moments in pitch, yaw, roll planes to augment aerodynamic controls, especially in flight regimes where the aerodynamic forces are soft, for example at extreme angles of attack/yaw or during low speed approach to landing. Ref 1 by Moorhouse, and associates, indicated that an F-15 aircraft had been modified to incorporate pitch axis thrust vectoring. Other programs were discussed in the symposium round table discussions (ref 24) where combined pitch and yaw vectoring will be investigated, e.g. modified F-18 and the X-31 enhanced fighter maneuverability technology demonstrator, a joint US-German project.

Since the AGARD symposium, the Short Takeoff and Landing (STOL) and Maneuver Technology Demonstrator F-15 (ref1) has flown and achieved all the objectives associated with thrust vectoring/reversing that were described by Moorhouse, et al, (ref 1). The test program showed conclusively that the aircraft flight control system and the propulsion control system could be integrated to achieve significant improvements in performance, maneuverability and short field capability.

Mangold and Wedekind (ref 16) addressed some of the same issues as Ref 1, but with an emphasis on pitch vectoring at high angles of attack. There will be a much stronger need for yaw control at these conditions because the vertical tail fin is losing effectiveness. Pitch vectoring is needed especially for nose-down pitch control at high alpha. Thus pitch/yaw vectoring to augment controls is one of the key technologies to realize the benefits of enhanced aircraft agility discussed in the opening session of the symposium (refs 1 to 4). Ref 18, by Holmes, called special attention to the propulsion-control integration requirements for short takeoff-vertical landing (STOVL) aircraft designs. Correct simulation of engine and airframe is needed to evaluate hot gas reingestion, and controllability near the ground.

5. AIRCRAFT GROUND EFFECTS

The second major theme of the symposium, closely related to the first, was to investigate the influence of ground effects on aircraft aerodynamics and controls. The major influence is during landing of high performance combat aircraft, wherein controllability at high sink rates and in gusty cross-winds is often an issue. The aircraft lands on a "bubble" of air; the dynamic response of this bubble is influenced by the aircraft configuration, weight, lift and attitude, as well as by the ambient winds. In order to correctly simulate the interaction between this bubble of air and the aircraft, refs 18-23 seemed to agree that the dynamics of landing were important in order to establish controllability in a high performance combat aircraft; thus it is necessary to account for the sink rate when evaluating ground effects. The F-15 STOL/Maneuver Technology Demonstrator now has flight data which bears out this conclusion.

Ref 19 (Vidal and Deschamps) described a unique test facility at CEAT to evaluate ground effects. The model is guided along a test track over a surface of water. Tests on a Falcon 900 executive jet transport showed considerable influence of dynamic ground effects. Ref 21 (Cocquerez, et al) described a unique free-flight test method, with on-board measurement of forces to evaluate ground effects, including the presence of side gusts. Some interesting, non-linear effects were reported.

Ref 20 (Paulson, et al) concluded that significant differences can exist between ground effects obtained with and without rate of descent being included (dynamic vs static), especially if vectored or reversed thrust is used prior to touch-down and during roll-out. The authors found that including the appropriate rate of descent reduced the severity of ground effects compared to static testing. They also found that the use of a moving belt on the floor of the wind tunnel to eliminate the boundary layer was less important than simulating the rate of descent, in order to determine the correct controllability and lift effects near the ground. Ref 22 verified these general results for the X-29 configuration, and found that there was less change in lift due to ground effects when the rate of descent was simulated. There was also a nose down pitching moment for the X-29 when dynamic landings were made, which was not present during static landing simulations. Finally, ref 23 (Condaminas and Becle) reported on an investigation of ground effects for a large commercial transport (A320). Good correlation of forces compared to flight test was achieved when the wind tunnel floor boundary layer was energized by blowing. This could indicate that dynamic sink rate simulation is not as important for large aircraft as it is for small aircraft with low aspect ratio wings. In other words, the "air bubble" has less influence on the net lift and controllability of a large aircraft.

6. CONCLUDING REMARKS

Because of very high maneuvering rates and accelerations, dynamic stability is much more important than ever before, as is the understanding of the dynamics of controls including all the cross-coupling effects. In fact, the basic concept of stability derivatives may come into question in some very rapid non-linear maneuvers.

An expanded flight envelope of the aircraft will dictate an expanded controls envelope, requiring a search for favorable interference between control surfaces and wings in maneuvers.

The engine, and the force it produces, in both direction and magnitude, is becoming a major control force and moment producer, especially where aerodynamic forces are soft, such as at high angles of attack, or during short takeoff or vertical landing conditions; hence the need for flight-propulsion control integration.

Integration of the airframe and its weapon is extremely important. High angle of attack maneuvers, used to bring weapons to bear on the target, will be limited in their effectiveness if the weapons cannot be launched at these conditions. This is an area that needs much more research.

Understanding complex ground effects, dynamic as well as static, will be crucial to safe, routine operations of military and commercial aircraft.

In summary, the aerodynamics of combat aircraft controls and of ground effects was given a thorough treatment at the symposium. Complete details may be found in ref 24. These are tough problems, but were addressed by AGARD because stretching the combat maneuver envelope will enhance offensive and defensive combat capability. By combining ideas and talents throughout NATO, by means of AGARD, we can collectively develop a superior technology base for combat aircraft of the future.

7. RECOMMENDATIONS

Analysis and test of three-dimensional control shapes should be continued to search for means to expand the safe maneuvering envelope of combat aircraft and weapons in order to increase offensive and defensive combat capability.

Dynamic and static stability evaluations should be conducted on complete configurations using new rotary balance and forced oscillation techniques to determine non-linear control effectiveness over the complete range of maneuvers, including post-stall and high rate (enhanced agility) conditions.

Increased emphasis and resources should be put on time-accurate unsteady flow computational fluid dynamics solutions with appropriate turbulence models, and applied to practical three-dimensional configurations at extreme maneuvers.

Innovative techniques, such as boundary layer and vortex control through blowing, suction and geometrical variations, should be pursued through full-scale flight test so that they can be used with confidence in future combat aircraft designs.

These recommendations should be pursued to the extent possible through collaborative efforts among the AGARD/NATO member nations.

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14. Abstract

The papers presented at the AGARD Fluid Dynamics Panel Symposium on "Aerodynamics of Combat Aircraft Controls and of Ground Effects" are summarized and evaluated. The reviewer also provides some general conclusions relative to the effectiveness of the symposium in addressing the problems of aerodynamics of combat aircraft controls and ground effects in an era when a stretched combat maneuverability envelope is needed to enhance both offensive and defensive combat capability. Recommendations for future experimental and computational fluid dynamics activities are also provided.

The papers presented at the meeting have been collected in AGARD CP-465 (AD-A223 680).

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